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SciVerse ScienceDirect
Energy Procedia 37 (2013) 3068 – 3088
Energy Procedia

GHGT-11

Integration of Pipeline Operations Sourced with CO_2 Captured at a Coal-fired Power Plant and Injected for Geologic Storage: SECARB Phase III CCS Demonstration

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Abstract

This paper presents a case study of the design and operation of a fit-for-purpose pipeline sourced with "anthropogenic" carbon dioxide (CO_2) associated with a large-scale carbon capture and storage (CCS) Research & Demonstration Program located in Alabama, USA. A 10.2 centimeter diameter pipeline stretches approximately 19 kilometers from the outlet of the CO_2 capture facility, located at Alabama Power Company's James M. Barry 2,657-megawatt coal-fired electric generating plant, to the point of injection into a saline reservoir within Citronelle Dome.

The CO_2 pipeline has a 6.5 meter wide easement that primarily parallels an existing high-voltage electric transmission line in undulating terrain with upland timber, stream crossings, and approximately 61,000 square meters of various wetland types. In addition to wetlands, the route transects protected habitat of the Gopher Tortoise. Construction methods included horizontal drilling under utilities, wetlands, and tortoise habitat and 'open cutting' trenching where vegetation is removed and silt/storm-water management structures are employed to limit impacts to water quality and ecosystems. A total of 18 horizontal directional borings, approximately 8 kilometers, were used to avoid sensitive ecosystems, roads, and utilities.

The project represents one of the first and the largest fully-integrated pulverized coal-fired CCS demonstration projects in the USA and provides a test bed of the operational reliability and risk management for future pipelines sourced with utility CO_2 capture and compression operations sole-sourced to injection operations. An update on status of the project is presented, covering the permitting of the pipeline, risk analysis, design, construction,

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doi:10.1016/j.egypro.2013.06.193

commissioning, and integration with compression at the capture plant and underground injection at the storage site.

Keywords: Carbon Capture and Storage; CO_2 Pipeline; SECARB, Geologic Storage; Citronelle Oil Field

1. Introduction

Over the past decade, significant research and development (R&D) has been focused on the commercial readiness of carbon capture and storage (CCS). CCS is a promising environmental controls technology for mitigating greenhouse gas (GHG), specifically carbon dioxide (CO_2), emitted by large industrial point sources such as coal-fired power plants. Electric utilities are currently looking at CO_2 sequestration in a wide range of geologic formations but are primarily interested in deep saline reservoirs and the utilization of CO_2 in enhanced oil recovery (CO_2-EOR) [1]. Deep saline reservoirs in the Southeast USA and oil fields have reservoir characteristics suitable for storage of the large volumes of CO_2 (>1 million metric tonnes per year) anticipated to be captured at coal-fired power plants [1].

Beyond the focus on capture and injection technology, utilities are especially interested in the design, cost, and reliability of CO_2 pipelines. CO_2 can be transported in different physical states including gas, liquid, or solid and can be accomplished in a number of ways – via pipeline, vessel, rail, or by truck [2]. Given the volumes of CO_2 that will be required to be captured by electrical utilities, transport under pressure as a liquid in pipelines will be the most cost effective method for most commercial projects. With approximately 7,000 kilometres of liquid CO_2 pipelines already in place worldwide, design and operational considerations are commercially mature in the CO_2-EOR industry. To date, little operational experience exists with pipelines transporting 'captured' CO_2 (also known as anthropogenic CO_2) sourced from coal-fired power stations. Even though regional CO_2 pipeline networks already operate commercially for CO_2-EOR, operators of utility carbon capture systems need to understand integration issues less common in business-as-usual CO_2-EOR [3]. These issues include planned and forced plant outages, load following, fuel dispatch and CO_2 purity.

The R&D program is an integral component of a plan by Atlanta-based Southern Company, and its subsidiary, Birmingham-based Alabama Power Company, to demonstrate the integration of capture, transportation, and geologic storage of CO_2 sourced from a coal-fired utility boiler. The capture facility is located at Alabama Power's 2,657-megawatt James M. Barry Electric Generating Plant (Plant Barry) located in Bucks, Alabama, USA (Figure 1). The project represents one of the first and the largest fully integrated pulverized coal-fired CCS projects in the USA, with the plant designed to capture up to a maximum of 550 metric tons per day, corresponding to 182,500 metric tonnes per year. However, a more realistic operating goal is to capture CO_2 at a rate of approximately 55 - 82 percent of the design conditions, which would be in the range between 100,000 and 150,000 metric tonnes per year.

The CO_2 captured will be transported by pipeline for injection into a saline geologic formation in Citronelle Dome (a salt cored anticline located in South Alabama, USA). The Citronelle Oil Field (Citronelle Field) is located at the crest of Citronelle Dome surrounding the City of Citronelle, Alabama, USA. Capture operations started at Plant Barry in June of 2011 with over 100,000 metric tonnes of CO_2 most of which has been captured and released to the atmosphere as of October 15, 2012. Since August 20, 2012, when pipeline commissioning was completed, approximately 10,000 metric tonnes of CO_2 have been transported via the CO_2 pipeline and injected into a saline formation in Citronelle Dome.

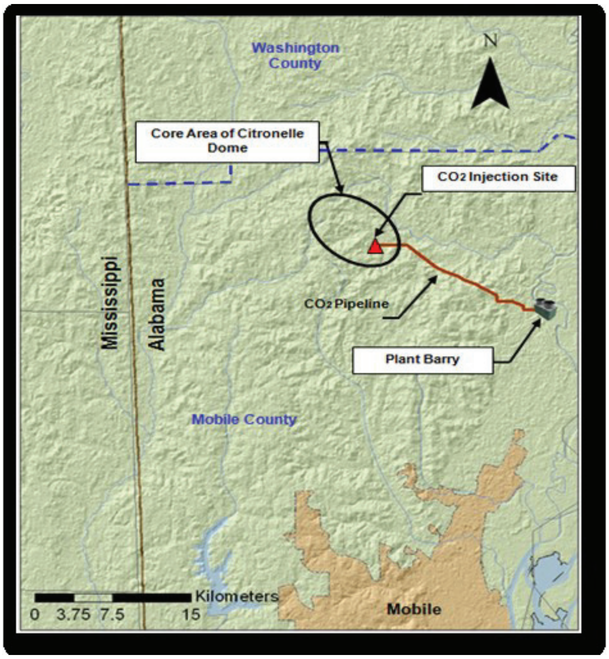

Fig. 1. Location of Alabama Power Plant Barry with connecting CO_2 pipeline to Citronelle Dome.

Citronelle Field is owned and operated by Denbury Onshore LLC (Denbury), an independent oil company who owns the largest geologic reserves of CO_2 for tertiary oil recovery east of the Mississippi River. Downstream injection operations for storage are into a saline reservoir (the Cretaceous age Paluxy Formation) located at approximately 3,000 meters below ground surface but stratigraphically above the oil reservoirs of Citronelle Field. The injection and storage operations of the project are being managed by the Department of Energy's (DOE) Southeast Regional Carbon Sequestration Partnership (SECARB) in a program to validate the feasibility of injecting, storing, and monitoring large volumes of CO_2 in geologic formations. Injection operations will continue for at least 2 years into 2014, with subsurface monitoring of the injected CO_2 continuing through 2017.

2. Systems development and design

2.1 General

A 10.2 centimeter diameter fit-for-purpose pipeline stretches approximately 19 kilometers from the outlet of the CO_2 capture facility at Plant Barry to the point of injection at Citronelle Dome. It was constructed of standard API 5L X-65 grade pipe with wall thickness between 0.48 and 0.56 centimeters. The pipeline has a 6.5-meter wide permanent easement that primarily parallels an existing high-voltage electric transmission line, crossing nine landowner properties having significant tract acreages. Some of the larger tract owners include Alabama Power Company, a timber company, a bank managed land trust, and Denbury. The route passes over undulating terrain with upland timber, stream crossings, and approximately 61,000 square meters of various wetland types. The injection wells and surface facilities are located on a 65 hectare piece of property owned fee simple by Denbury.

In addition to wetlands, the route transects protected habitat of the Gopher Tortoise, which is drawn to the open sandy terrain of well-maintained transmission line easements. Construction methods included horizontal directional drilling (HDD) under utilities, wetlands, and tortoise habitat and 'open cutting' where vegetation is removed and silt/storm-water management structures are employed to limit impacts to water quality and ecosystem habitat. A total of 18 inclined horizontal borings (approximately 8 kilometers in total length) were used to avoid sensitive ecosystems, roads, and utilities.

2.2 CO_2 Capture Technology and Purity

Two separate CO_2 purity considerations are in play for the project, including: 1) analysis required for compliance with the Class V Underground Injection Control (UIC) permit; and 2) specifications for pipeline integrity, established by the CO_2 shipping agent. The UIC purity/sampling requirements full fill several different objectives including: 1) make certain the project is not injecting a hazardous substance along with the CO_2; 2) protect Underground Sources of Drinking Water (USDWs); and 3) maintain injection well integrity.

For the UIC permit specific composition parameters must be characterized monthly in the injection stream. These parameters include percent (%) carbon dioxide (CO_2), oxygen (O_2), and nitrogen (N_2). On August 28th, 8 days after starting up the transportation and injection operations, a sample of the injectate stream was collected at a metering station which is located approximately 1 mile from the capture facility. This is also the location of the custody transfer of the CO_2 from Southern Company to Denbury Resources where they do a monthly total analysis of the CO_2 in the pipeline. The total analysis of the CO_2 includes purity, impurity gases that include H_2, He, O_2 + Ar, N_2, CO, NH3, total hydrocarbons, total non-methane hydrocarbons, and many other compounds. Based on the results of the analysis, the injectate stream contained 99.9+% CO_2 (v/v), 38 parts per million or 0.004% (v/v) O2 (plus argon), and 210 parts per million or 0.021% N_2 (v/v). Pipeline integrity requirements established by Denbury, in the carbon capture project's off-take agreement, are specified as 97% CO_2 on a dry basis, less than 20 ppm H_2S, less than 35 ppm total sulphur, less than .5% inert components (including argon and nitrogen), less than 2 ppb mercury, and less than 30 lbs per 1,000 MCF water vapor.

The CO_2 capture technology uses the Kansai Mitsubishi Carbon Dioxide Recovery Process (KM-CDR) which is licensed by Mitsubishi Heavy Industries America (MHIA). The KM-CDR process has been demonstrated at smaller scale at a coal-fired generating station in Japan, and is currently being deployed commercially on natural gas-fired systems around the world. The technology utilizes the proprietary KS-1 solvent to achieve high levels of CO_2 retention with significant reductions in energy penalty compared to other post-combustion carbon capture technologies [4] [5]. The process produces high purity CO_2 (>99.9%), an important environmental consideration for transport and injection operations. The quality of the CO_2 produced at the facility by design meets the following criteria: the maximum temperature is 120F, the maximum level of N_2 is 4 vol% (dry), the maximum level of total hydrocarbons is 5 vol% (dry), the maximum amount of H_2O is 30 lb/MMSCF, and the minimum CO_2 purity is 95 vol% (dry). The design pressure at the battery limit of the carbon capture and compression island is 1500 psi which enters the pipeline to be transported to the injection site. The design temperature at the battery limit of the capture facility is 113F as the CO_2 enters the pipeline. This temperature and pressure ensures that the CO_2 leaving the capture facility and to the pipeline is supercritical.

2.3 Risk Registry and Management

For CCS to mature commercially with electrical utilities, the operational reliability of transportation must be integrated with upstream capture plant operations and downstream injection into saline reservoirs. A challenge associated with CCS is the need to ensure proper management of risks along the full CCS chain of capture, transportation, injection, and monitoring, and, in particular, implementation of the precautions necessary to ensure the reliability of the entire set of integrated operations.

Within the United States, guidelines and best practice manuals are being developed for risk management within the CCS community. Within the international CCS community, several guidelines and standards have been developed, or are in the process of development. Documents that have provided guidance for the risk management approach taken by the Project team include the following:

- ISO 31000 (ISO 31000: Risk management – Principles and Guidelines 2009) [6]
- DNV-RP-J201 (DNV-RP-J201: Qualification Procedures for CO_2 Capture Technology 2010) [7]
- DNV-RP-J202 (DNV-RP-J202: Design and Operation of CO_2 Pipelines, 2010) [8]
- World Resources Institute (WRI) CCS Guidelines – Guidelines for Carbon Dioxide Capture, Transport, and Storage [9]
- CO_2QUALSTORE – Guideline for Selection and Qualification of Sites and Projects for Geological Storage of CO_2 [10]
- Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide, Guidance Document 1 – CO_2 Storage Life Cycle Risk Management Framework, 2011 [11]
- Best Practices for: Risk Analysis and Simulation for Geological Storage of CO_2 (NETL 2011) [12]
- CSA Z741: Geological Storage of Carbon Dioxide 2012 [13]

A project risk registry identifying a total of 48 different risks was developed as a focus for the CCS components of the value chain (capture, transport by pipeline, storage, and monitoring), including the integration of these components. Prior to creating the project risk register, the elements of concern and the risk evaluation criteria were defined. The following elements of concern were defined: health and safety; environmental protection; cost; reputation; and start-up of integrated operations. The risk evaluation criteria were expressed in terms of a combination of the "qualitative" likelihood of occurrence, and the corresponding severity of potential impact.

Developing a "unified" risk register for integrated projects in which risk ownership (and project responsibility) is shared among different corporate entities presents several challenges. The different companies involved may have different corporate risk management procedures and guidelines. Information about risk, in particular financial and economic risk, can be business sensitive, so the participating companies may not be willing to share such information unless it is part of the contractual agreement, or unless the information is critical to ensure robust and reliable operations.

None of the risks identified by the project team were determined to be unacceptable. Some risks were found to be in the "tolerable" band when appropriate safeguards and/or mitigating steps were implemented. The highest rated risk scenarios relate to regulatory uncertainty and to successful integration of project components (capture, transportation, injection, and monitoring.) The highest rated risk for CO_2 transportation arises from the possibility of third party damage to the dedicated pipeline.

2.4 Source Integration

With approximately 7,000 kilometres of CO_2 pipelines in place worldwide, design and operational considerations are commercially mature as related to the CO_2-EOR industry. To date, very little operational experience exists with pipelines transporting 'captured' CO_2 sourced from coal-fired power stations. Electric utility CCS business models, driven by costs, will strive to optimize injection into fewer injection wells in contrast to commercial-scale CO_2-EOR operations. This will be especially prevalent with a single source of CO_2 coupled to a dedicated local saline reservoir. The CO_2 transportation component of the Project's single source – single sink network proved to be a key element of the business integration process. For CCS to mature commercially with electric utilities, the operational reliability of transportation must be integrated with upstream capture plant operations and downstream injection into saline reservoirs. Operational issues include planned and forced outages, load following, and potential changes in CO_2 purity coupled with disruptions in transport and injection operations, such as forced and planned well and pipeline maintenance.

The CO_2 transportation provider must comply with pipeline regulations but must also be able to conform to the legal, regulatory, and technical frameworks under which the CO_2 capture unit and the CO_2 storage field must operate. Projects that are developed as single source – single sink business propositions will face new challenges that have not been experienced by the CO_2 pipeline industry which, traditionally, has supplied CO_2 via a pipeline network for commercial use. Field demonstration projects, like the SECARB Anthropogenic Test, provide valuable insight and experience that will be needed to shape future commercial integrated CCS operations.

3. Environmental permitting

National Environmental Policy Act (NEPA) permitting was required to be completed and approved by the DOE before the project was able to begin. The essential purpose of NEPA is to ensure that environmental factors are weighted equally when compared to other factors in the decision making process undertaken by federal agencies. An Environmental Assessment (EA) was required to be performed for both the injection site and for the pipeline. Extensive environmental coordination, permitting, and inspection services to support the pipeline was performed between 2010 to 2012.

Project coordination included consultation with various federal, state, and local environmental agencies. Based on the results of pre-project coordination, permitting efforts focused on the Alabama Department of Environmental Management (ADEM), the Alabama Historical Commission (AHC), the State Historic Preservation Office (SHPO), the U.S. Fish and Wildlife Service (FWS), and the U.S. Army Corps of Engineers (USACE). Project areas covered by the permitting activities included approximately19.5-meters-wide of proposed nominal 12.2-meters-wide construction right-of-way encompassed by a 29-meter-wide survey corridor, extra workspaces, access roads, contractor yards, well pads, oil flow lines, and electrical transmission lines. The wider survey corridor and associated permitting were designed to facilitate minor re-routing of the pipeline to avoid sensitive resources if required.

3.1 Hydrostatic Test Water Discharge

New pipelines are typically filled with water and then pressurized to check for leakage prior to being placed in service. Project staff coordinated with ADEM regarding compliance with their Hydrostatic Test Water Discharge General Permit. General NPDES Permit Number ALG6700000 authorizes discharges resulting from the hydrostatic testing of pipelines within Alabama as administered by ADEM. Project staff prepared and submitted a Notice of Intent (NOI) for this permit, providing operator, facility, location, and discharge information for each proposed test water discharge. The discharge plan included basic information on dewatering structures and procedures to prevent scour or other potential impacts. Additionally, non-chlorinated test water was used to protect aquatic life in streams and wetlands located near the upland discharge points. The Project team coordinated closely with local regulatory agencies during the period of multiple discharges in order to provide the proper pre-discharge notifications.

3.2 Stormwater Management

As a construction project that disturbed more than one acre of land, the proposed pipeline was subject to ADEM's National Pollution Discharge Elimination System (NPDES) storm water registration. An environmental consultant was retained to design and manage erosion and sediment control planning, to complete the ADEM Notice of Registration (NOR) prior to construction. As a part of the NOR, a Construction Best Management Practices Plan (CBMPP) that outlined the proposed Project, erosion and sediment control best management practices (BMPs), good housekeeping BMPs, post-construction BMPs, inspections, and recordkeeping was prepared.

3.3 Cultural Resources

A Phase I field survey, in accordance with the Alabama SHPO standards consisting of near-surface shovel testing in undisturbed portions of the right-of-way that exhibited high or moderate potential for near-surface archaeological sites, was guided by reconnaissance and background research results. Shovel test pits (STPs) were excavated at 100-foot and judgmental intervals in these locations. When a potential archaeological site was discovered during this procedure, excavated radial shovel test pits at reduced 10-meter intervals around positive STPs were conducted to evaluate artifact discoveries and to delineate site boundaries within the right-of-way. The shovel tests typically extended to a maximum average depth of 0.49 meters. Following completion of the field surveys, reports detailing the results of the field investigations were written and submitted to the SHPO requesting concurrence with the findings of the cultural resources investigations pursuant to Section 106 of the National Historic Preservation Act. No significant cultural resources requiring avoidance and/or mitigation were encountered during the surveys, and the AHC-SHPO approved the Project contingent that any unexpected finds of archaeological or historic resources during construction would require additional consultation. Construction proceeded without incident and no unanticipated archaeological resources were encountered.

3.4 Endangered Species

The project team collected qualitative information relative to existing habitats and species communities that existed along the pipeline right-of-way and related areas. The database of the Alabama Natural Heritage Program (ANHP) was reviewed for records on known occurrences of any federally- and/or state-listed threatened or endangered species located in proximity to the proposed project. Consultation with the FWS and Alabama Department of Conservation and Natural Resources (ADCNR) was also conducted. Three federally-listed species, red-cockaded woodpecker (Picoides borealis - endangered), eastern indigo snake (Drymarchon corais couperi - threatened), and gopher tortoise (Gopherus polyphemus - threatened) were identified as potentially occurring within the proposed Project area based on available habitat. Information on the ecology and Southeastern recovery plan for the Gopher Tortoise is provided [14].

Following the collection of background data, reconnaissance-level field evaluations were performed of the survey corridor and associated areas to gather information. Project team biologists employed a global positioning system (GPS) instrument capable of sub-meter accuracy, to record and geographically reference significant environmental features within the Project assessment area. Pertinent information such as species observed, species-specific habitat and signs, land-use type, wetlands, and vegetation communities observed, as well as distinct changes in the surrounding area, was documented on field maps and notes. Photographs were obtained to document representative habitats, vegetation, and land uses. To further evaluate the potential presence of gopher tortoises and/or eastern indigo snakes, biologists initially conducted meandering pedestrian observation transects through all of the assessment corridors. Identified gopher tortoise burrows were categorized as active, inactive, or abandoned and their positions were recorded using the GPS.

Following this first phase of reconnaissance-level assessment and based on the finding of numerous gopher tortoise burrows, as described below, a second phase of intensive survey for gopher tortoises and burrows was performed by qualified scientists. BVA is federally licensed to conduct gopher tortoise studies, including the scoping of tortoise burrows via camera to assess their status and condition. BVA focused their follow-up survey in areas where evidence of gopher tortoise burrows had been observed in the initial assessment.
The following tasks were performed during the second phase field survey:

- Gopher tortoise burrows previously identified and numbered were located again using GPS coordinates and maps and were re-examined;
- Suitable habitat areas in the right-of-way were resurveyed and the location of all gopher tortoise burrows not identified during the initial survey were also recorded with sub-meter accuracy GPS equipment;
- A determination was made of the age class of each burrow (i.e. adult or juvenile); no differentiation was made between adults and sub-adults;
- The activity status of each burrow (i.e. abandoned, inactive, active) was determined by making a visual assessment of the condition of the apron and mouth of the burrow;

- Each adult tortoise burrow was scoped with an infrared camera to determine if the burrow was occupied; and
- Where possible, the length, depth, directional orientation, and end point of each burrow (or the location of the tortoise in the burrow) were documented by utilizing a tracking beacon attached to the scoping camera. The beacon sent a signal to a tracker/receiver that gave a ground level indication of the beacon location, and that point was then entered in the GPS. The bearing between the mouth and the end point of the burrow was also noted.

No eastern indigo snakes or red-cockaded woodpeckers, nor signs of their presence, were observed. Additionally, no gopher tortoises were observed during reconnaissance field assessments. However, a total of 51 gopher tortoise burrows were found in the Project area. Forty eight of these burrows were observed along a portion of the proposed route that is collocated with the existing transmission line right-of-way and an abandoned oil pipeline right-of-way. Those burrows were typically associated with the grassy existing easement or the adjacent tree line. A few burrows also were observed in the adjacent forested upland clay hills. A representative photograph of a gopher tortoise burrow observed in the Project area is included as Figure 2.

Fig. 2. Gopher tortoise burrow observed near the Plant Barry to Citronelle pipeline.

Based on extensive consultation with the FWS, the Project was allowed to move forward under informal consultation regarding potential impacts to the gopher tortoise. The avoidance of formal consultation, which would have been triggered if active burrows would have been damaged during construction or if tortoise relocation was required, resulted in significant time and cost savings for the Project. Additionally, the impact avoidance and mitigation measures described below provided a high level of protection for the gopher tortoise and its burrows and habitat. A photograph of a gopher tortoise observed in the Project area during construction is included as Figure 3.

Fig. 3. Gopher tortoise observed near the Plant Barry to Citronelle Pipeline.

A series of measures were designed to avoid impacts to the gopher tortoise. These measures included:

- Use of horizontal directional drills (HDD) to drill under burrows that were located in the path of the proposed pipeline;
- Plans for the use of contingency HDD(s) in the event that unanticipated, active burrows were subsequently found in the path of construction;
- Use of barrier fencing (e.g., wire-backed silt fencing) to provide adequate separation between burrows that were located near the proposed pipeline and work areas;
- Reductions in construction right-of-way width (i.e., neckdowns) to aid in proper separation distances;
- Expeditious construction with pipeline installation and trench backfill following as soon as possible after clearing, to limit the opportunity for tortoises to enter the work areas;
- Training for the environmental inspectors and construction staff regarding the appearance of gopher tortoises and their burrows, and the protected status of the species;
- Daily and ongoing inspections, and awareness by the construction environmental inspectors and construction staff, regarding tortoises and/or burrows that may be observed in or near the work areas;
- Utilization of an “on call”, local, federally-licensed gopher tortoise contractor who could remove a tortoise from a work area or examine and scope a newly-found burrow, if needed;
- Use of a Project speed limit of 32 kilometers per hour for all vehicles, except as posted on county or state maintained roads, to aid in the avoidance of traffic-related impacts, as well as driver training regarding the appearance of gopher tortoises and their burrows, and the protected status of the species;
- Use of a Project “no harm” policy for wildlife, including any turtle or tortoise; and
- Limitation of mowing of the permanent right-of-way until the coldest winter months (i.e., December, January, or February) when tortoises are least active, and training of Project maintenance staff regarding the gopher tortoise and its protected status.

Using these measures, which were accepted by the FWS in the permit granted, the project was able to successfully avoid impacts to the gopher tortoise during construction.

3.5 Waterbodies and Wetlands

The Project required authorization by the U.S. Army Corps of Engineers (COE) under Section 404 of the Clean Water Act (CWA), for the crossing of federal jurisdictional wetlands and waters of the United States. The project team performed jurisdictional waterbody and wetland delineations along the pipeline and associated areas. All delineations were conducted in accordance with the COE 1987 Wetlands Delineation Manual. A Wetland Delineation Report was prepared for submittal to the COE Mobile District, documenting the waterbody and wetland delineation findings for the proposed pipeline project and associated areas. A Nationwide Permit 12 (Utility Line Activities) was used to authorize all waterbody/wetland impacts associated with construction of the proposed pipeline and associated areas. Project authorization included the development and submittal of a pre-construction notification (PCN) to the COE. CWA Section 401 Water Quality Certification authorization was based on review of the PCN by ADEM. Twenty-nine waterbodies were identified that would be crossed by the proposed pipeline. Additionally, approximately 4.5 hectares of wetlands were affected by construction of the proposed pipeline and associated facilities, although no wetlands were filled or permanently lost. About 3.4 hectares of the wetland impacts were to palustrine forested wetlands (PFO).

To reduce direct waterbody impacts from pipeline construction, nearly half of all waterbodies (14 waterbody crossings) were avoided via HDD. The remaining waterbody crossings were accomplished via open-cut methods. To minimize impacts to forested wetlands the pipeline was collocated along existing cleared rights-of-way for approximately 66 percent of its length (approximately 12.8 kilometers). In collocated areas, impacts to forested wetlands were further minimized by overlapping temporary workspace with pre-existing, cleared rights-of-way. The pipeline also crossed 15 wetland areas via HDD. The use of HDD in these areas resulted in the avoidance of surface impacts to these wetlands. To compensate for the conversion of PFO wetlands to emergent or scrub-shrub wetlands along maintained portions of the right-of-way, wetland mitigation credits were purchased from a COE-approved mitigation bank. Collectively, these significant waterbody and wetland impact avoidance, minimization, and mitigation measures served to effectively protect these valuable resources.

3.6 Environmental Inspections

Two environmental inspectors were utilized during and after construction to ensure compliance with the environmental permits. Primary duties of the inspectors included monitoring of the project’s sediment and erosion control measures in accordance with the ADEM stormwater management permit, coordination regarding installation, use, and maintenance of the protective measures for the gopher tortoise, and compliance with the protective measures required for the crossing of waterbodies and wetlands. The environmental inspectors also trained all of the project construction staff regarding the environmental permitting requirements of the Project. Working with the entire Project team, the environmental inspectors were able to maintain a high level of compliance with the Project’s permit standards.

4. Right-of-way

4.1 Easement Requirements

Construction of pipelines requires both permanent and temporary rights-of-way (ROW) to allow adequate work space for construction equipment and personnel access, trenching and boring activities, dirt spoil from trenching, pipe layout (stringing), and welding. The width of the required ROW, both permanent and temporary, depends on multiple factors, including the diameter of the pipeline, type of terrain, landowner sentiment and price requirement, population density, agricultural usage, potential impacts to protected species, adjacent utilities and easements, ability to use eminent domain, and type of construction method employed on a particular tract. Working widths range from 9 to 46 meters and vary from project to project. The costs and conditions of purchase are negotiated with each landowner and are reflective of the normal use of the property, family member input, lost future production for agricultural properties, and previous history with other utilities.

The CO_2 pipeline traverses approximately 19 kilometers over a predominantly rural, wooded landscape with rolling hills and sandy soils. Approximately one additional mile lies within the Plant Barry operating unit and is maintained by Alabama Power Company. A significant portion of the Denbury route outside the plant parallels a high voltage transmission corridor and an abandoned crude-oil pipeline with commercial timber acreage to either side of the corridor. Residences were limited along the route and typically not located within 61 meters of the pipeline. As mentioned in the permitting section, the project also encountered colonies of endangered gopher tortoise, which have an affinity for sandy soil in sunny areas that are routinely found in the utility corridors along the route. Routing of the pipeline adjacent to other utilities lessened the impact to area landowners and the commercial timber but also presented some construction constraints due to an overabundance of gopher tortoise burrows within and adjacent to the ROW. The abandoned crude-oil line presented additional challenges, as the sandy soil had eroded in many areas and exposed the other pipeline. The movement of heavy equipment parallel to this pipeline presented a safety risk that required special visual indicators and additional soil cover over the line to prevent any possible damage to the abandoned line. After consideration of each aspect above, the temporary ROW for the pipeline was 12 meters in width for areas of trenched construction and 18 meters for the horizontal directional drills (HDDs) and horizontal bores. The permanent ROW is 6 meters in width.

4.2 Care and Control

After construction, the ROW was restored to the original contours with slope breakers and Curlex (stabilization netting) installed in steeper areas where erosion potential is high. The ROW was seeded with a mixture of Bahia, Bermuda, and Rye grass and fertilized to quickly establish ground cover. The temporary ROW will be allowed to return to its native state and no longer used for access. Portions of the line installed by HDD pass under sensitive wetland and gopher tortoise areas; these areas will not be cleared and will be maintained in the natural state to minimize impacts. The 6-meter permanent ROW will be maintained vegetated but cleared of trees in all trenched and bored areas. These areas will be kept mowed to facilitate visual inspections on the ground and via aerial flight, as required by the Code of Federal Regulations 29 CFR 195 for liquid pipelines.

Weekly aerial flights are employed to inspect for possible construction or development on or near the pipeline ROW, as well as to look for possible leaks on the pipeline. Visual inspections will also be conducted of the pipeline route on the ground. These inspections will confirm any aerial reports of suspected construction activity, look for erosion or other ROW damage, and ensure that no one has tampered with the mainline valve station along the route. Each inspection is documented, per federal requirements. Issues identified during the inspections will be handled starting with the initiation of discussions with a landowner who may be impacting the ROW (for example, locating a mobile home within the easement).

4.3 Decommissioning and Abandonment

At some point, every pipeline meets the end of its service contract or useful life and must be decommissioned and abandoned. Requirements for abandonment vs. simply being "out of service" depend on the state of operation (Alabama in this case), landowner requirements, and possible use by another interested party for converted service. For the CO_2 pipeline, each landowner stipulated its own abandonment clause or accepted what was included in the ROW document provided. Listed below is a summary of the abandonment/term limit clauses found in the executed and recorded ROW agreements for pipeline easements.

- ROW reverts to landowner 12 months after operations are discontinued or 60 months from date agreement was granted (whichever comes first).
- Abandonment defined as 60 days after discontinued use.
- Abandonment defined as 24 continuous months of non-use.
- Abandonment not expressly defined but terms of abandonment are addressed.

Abandonment of the pipeline in place is allowed under each easement agreement, however, any aboveground appurtenances, such as a valve and its associated piping, must be removed. Conditions of abandonment vary in each state but typically require all product be removed from the pipeline and the line filled with an inert gas (i.e., nitrogen) or substance (i.e., cement). The cathodic protection system is disconnected and the steel left to interact with the surrounding natural elements (soil and water). The easement is dissolved and pipeline ownership reverts to the landowners. Line markers used to identify the pipeline's location may be left in place or removed at the landowner's discretion.

5. Construction techniques

5.1 Horizontal Directional Drill

HDD was an important and necessary technique utilized in the installation of the pipeline. While the pipeline covers a relatively short distance of 19 kilometers, many portions presented obstacles that dictated the use of HDD to minimize impacts to protected animal species, reduce risk to adjacent utilities or construction personnel, jurisdictional wetlands, and to reduce cost. The entire project utilized a total of 18 HDD drills. The first mile of the route lies within the Plant Barry operating unit and navigates under a cooling water canal, parking lots and entrance roads, plant utilities, and multiple transmission tower guy wires in a tight corridor. Rather than trench the pipeline through these congested areas, HDD was selected as the method that would pose the least amount of risk to the many utilities in operation and minimize impacts to personnel parking and access and egress to and from the plant. Three HDDs were performed inside the power plant site at a considerable cost savings relative to trenching and hand digging. The total depths of the HDD were all between 12 to 18 meters below ground surface.

Fifteen HDDs were performed along the remainder of the route and used most often to minimize impacts to jurisdictional wetlands and avoid gopher tortoise burrows or colonies. The gopher tortoises are protected and cannot be disturbed or relocated without significant expense and employment of a federally licensed tortoise wrangler. For this project, it was more economical to horizontally drill 9 to 12 meters under the tortoise colonies than to tree and relocate the tortoises or deviate from the utility corridor into the commercial timber area, where additional monetary damages must be paid for removal of trees. Other HDDs were used to cross under a railroad track and highway, as well as under extremely wet areas with limited and difficult access. Figure 4 shows drilling in progress for the pipeline installed using HDD under Alabama Highway U.S. Route 43 in Mobile County, Alabama.

Fig. 4. Horizontal Directional Drilling under Alabama Highway U.S. Route 43.

5.2 Trenching

In areas where there are few obstacles to be avoided, trenched construction is preferred and less costly than other methods of pipe installation. The type and required width of a pipeline trench is determined by the type of soil, its water content, and the ability of the soil to maintain an open, safe trench for entry by personnel during the pipe installation. The small diameter of the pipeline would lead many to consider possible use of an automated trenching machine, which provides a continuous box-shaped trench (no sloped sides), as a less costly method than conventional trenching. However, the sandy nature of the soils prevented using this technique, due to the threat of possible trench cave-ins, and necessitated conventional trenching methods using track hoes for excavation.

The majority of the pipeline route was installed in an arch key-shaped trench 1.2 to 1.5 meters deep, 0.6 meters wide at the bottom, and 2.1 to 3 meters wide at the top of the ditch with the width depending on local soil conditions. Figure 5 shows a typical location of the pipeline that was installed using trenching parallel to Alabama Power's 115 kV high voltage transmission line. The close proximity of high voltage transmission and power distribution lines required the use of alternating current (AC) mitigation to reduce the threat of future corrosion damage to the pipeline. Construction specifications require that the pipe fusion bond epoxy coating have no holes before burial of the pipeline, and construction inspectors are charged with ensuring any holes found be repaired with a 2-part epoxy. Should any holes remain after burial of the line and mitigative measures are not employed, the induced current will concentrate on the exposed metal and eventually 'cut' a hole into the line. To counteract any potential high voltage effects on the pipeline, a bare copper cable was buried parallel and adjacent to the pipeline in the open trench to provide grounding to reduce the induced A/C voltage. The HDD sections do not have the copper cable installed, as it is extremely difficult to pull the cable through the hole with the pipe without damaging or severing the cable.

Fig. 5. Pipeline trenching paralleling the existing high voltage transmission line.

6. Commissioning

Pipeline commissioning refers to the process or steps required to initially pressurize the pipeline with CO_2, allowing the pipeline to be placed into permanent service. The commissioning process involved preparation and implementation of an integrated pipeline commissioning plan with emphasis on worker health, public safety, and environmental protection. The detailed pipeline commissioning plan outlined the specific steps to be followed during start-up, the roles and responsibilities of organizations involved in pipeline operations, identification of key pieces of equipment and individuals involved in the commissioning process, sample collection procedures, and worker health and safety procedures.

The team responsible for plan preparation included Southern Company Services and Alabama Power Company engineers responsible for operating the power unit, capture plant, and compressor and Denbury Resources engineers responsible for the pipeline CO_2 booster pump operations for injection. The team held numerous conference calls to discuss start-up operations, identify key processes and equipment involved in the commissioning, and CO_2

sampling, monitoring, and analytical procedures required for regulatory compliance. The plan was developed using input from both organizations, relying on the knowledge and experience of both groups to produce an integrated written plan that could then be implemented with high likelihood of success. Draft and final versions of the written plan were circulated for engineering review and management approval for quality assurance purposes prior to implementation.

Implementation of the plan was accomplished in three phases, involving five individual segments of the pipeline, as listed below, including a 2-kilometer segment on the Plant Barry property, the Denbury custodial metering site located just west of the power plant, the17.7 kilometer pipeline to the booster pump, and the D-9-7 #2 wellhead located at the Citronelle Field.

- Start-up of CO_2 compressor and filling of pipeline on the power plant property (8 March 2012)
- Filling and calibration of the Denbury CO_2 custody meter (8 March 2012)
- Filling of the 17.7 kilometer pipeline and CO_2 check meter station (8 March 2012)
- Start-up and flow through the injection pump skid and CO_2 flow line (20 March 2012)
- Injection of CO_2 into Well D-9-7 #2 (20 August 2012)

Phases 1 and 2 were initiated during the week of March 4, 2012. Prior to filling the line with CO_2, an inert blanket of pressurized dry nitrogen gas (injected into the pipeline immediately following construction to prevent internal pipe corrosion) was vented to the atmosphere. Next, a blow down valve on the pipeline located at the custodial metering station was opened along with other key valves at the compressor. This allowed dry compressed CO_2 gas to be delivered to the custodial transfer station where it was temporarily vented, along with the residual nitrogen in the line, for approximately one hour, through the blow-down stack to the atmosphere. The CO_2 was delivered at an initial pressure of2.1-2.4 MPa. Once the pipeline was purged of nitrogen, it was filled with supercritical CO_2 at 10.3 MPa, then purged a second time, for approximately 20 minutes, before shutting the pipeline in to collect CO_2 samples for regulatory purposes.

CO_2 samples were collected at the custodial transfer station to characterize the gas composition, as required by the Alabama Department of Environmental Management (ADEM), who issued the underground injection control permit. US Environmental Protection Agency (EPA) standardized methods for collecting and analyzing supercritical CO_2 samples do not exist; therefore, modified EPA methods or methods employed by other industries, were adopted. Low-pressure grab samples were collected in Tedlar® gas sampling bags for offsite analysis. Subsequent analysis of the samples indicated that the gas stream contained 99.6% CO_2, 2,700 parts per million (ppm) N_2, 880 ppm O_2 and Ar, 12 ppm of non-methane hydrocarbons, and trace hydrogen. All measurements are reported on a volume of analyte per volume of sample (v/v) basis.

Metals analyses were also requested by ADEM, which are typically found in flue gases. CO_2 gas sample collection and analysis for metals used a modified version of US EPA Methods 4, 5 and 29, commonly used for low pressure particulate and metals emission testing of flue gases. The modification involved flowing CO_2 gas from the pipeline (instead of flue gas) through filters or impingers, allowing metals to accumulate in the extract, which was later analyzed for individual metals. Trace metals were detected in the CO_2 at very low concentrations (<0.003 ppm) using this approach.

After sample collection was completed, the second phase of the commissioning process began, consisting of filling the remaining 17.7 kilometers of pipeline from the custodial metering station at the plant property boundary to the check meter station at the injection site in the Citronelle Field. A similar procedure was used to purge and fill the pipeline with dry CO_2, after which the pipeline was shut-in until ADEM reviewed the CO_2 composition data and issued the final approval to inject CO_2, on August 8, 2012. On August 20, 2012, the third and final phase of the commissioning process was completed, consisting of purging and filling the short lines downstream from the check metering station through the booster pump and injecting CO_2 into the injection well, D-9-7 #2.

Careful planning and coordination of activities by Plant Barry and Denbury pipeline personnel resulted in a safe, successful pipeline commissioning campaign. Frequent communication between the groups was the key to providing constructive input to the plan, which contributed to its successful implementation. Significant effort was placed on identifying methods and analytical procedures that could be used to assess CO_2 composition. Low-pressure sampling and analytical procedures developed for other types of gases (e.g., flue gases) and applications (e.g., carbonated beverage industry) were used, but the accuracy and efficacy of these methods should be evaluated further by industry in the context of characterizing supercritical CO_2 composition for geologic storage projects.

6.1 Communications

In preparation for start-up, representatives from the operations, engineering, and control functions for the carbon capture unit, CO_2 pipeline, and injection components identified multiple scenarios that could affect overall operations and determined a communication structure and actions to be taken by specific personnel. The communication plan also provides notification procedures and contact information for key personnel responsible for each area of the capture, transport, and injection operations. As injection proceeds, the communications plan may be reviewed and adjusted to better address any shortcomings in the plan. Each component of the injection process requires a level of control and monitoring to ensure system conditions are within expected limits and that CO_2 is delivered for injection. The data required to accurately communicate conditions across the system were defined in the design and commissioning process and made available according to their relevance to each operation.

The CO_2 pipeline custody transfer meter, the point at which transfer of control and ownership of the CO_2 occurs, has the capability to monitor moisture content, mass flow rate, pressure, temperature, and composition. This information, and the status of the inlet motorized block valve, is communicated to a central control system via satellite where it is continuously monitored by trained personnel. The pipeline is also equipped with a check meter station located in the Denbury Citronelle operating unit. This meter is used to verify the volume of CO_2 delivered through the pipeline (a Federal requirement for jurisdictional pipelines) and confirm the volume of CO_2 injected into the formation. As with the custody meter, the volume, pressure, and temperature of the CO_2 are communicated via satellite to the pipeline control center and via hard wire to the injection pump for monitoring of the pump's suction side conditions. The pressure and temperature to the pump are used by the variable frequency drive to make adjustments to the speed of the pump, to set minimum suction pressure alarms to prevent damage to the pump, and to maintain the CO_2 in a supercritical state in the pipeline.

6.2 Capture Unit Integration

The CO_2 quality and operating condition data captured at the custody meter site are also shared with the capture unit control room to provide additional delivery status information to its operators. Sharing of this information allows the capture unit control operators to view the information simultaneously with the pipeline control operators. If quality changes, and approaches a predefined alarm set point, the nature and severity of the condition will be communicated by the pipeline control operator to the capture plant control center via phone contact. In turn, the plant will evaluate the time required to return the CO_2 quality to the required specifications and share this with the pipeline control operator. If the condition has potential to affect pipeline integrity, such as an abundance of moisture, the system may be shut in until the condition has been addressed. The necessity for shutting in the pipeline will be discussed between the pipeline control room and the operators of the carbon capture plant, to allow each party to understand the timelines for shutting in the system, addressing the upset condition, and restarting full operation.

6.3 Transportation and Injection Integration

The pipeline is integrated into injection operations by a General Electric CO_2 booster pump designed and fabricated by the Woods Group (Figure 6). The booster pump is approximately 13 meters long with 130 stages (impellers). The pump is equipped with a 300 horsepower, 3,570 rpm electric motor with variable speed drive and a recycle valve, for nearly 100 percent turndown. The pump has a 1.2-meter suction side with an inlet pressure of 8.96 MPa and a 0.91-meter discharge with an outlet pressure of 22.06 MPa, with the outlet leading to the D-9-7 #2 injection well, located approximately 20 meters from the pump. The pump has a stand-alone air compressor system to operate valves and controls. The maximum flow rate for the pump is approximately 14 MCFD.

Fig. 6. General Electric CO_2 booster pump located at the D-9-7 #2 injection well.

7. Discussion

Even though over 7, 000 kilometers of regional CO_2 pipeline networks already operate commercially, operators of utility CO_2 sourced CCS or Carbon Capture Utilization Storage (CCUS) projects will need to understand and address pipeline integration issues that are specific to the power industry and not commonly encountered by today's CO_2 EOR operators. Our pilot project includes all three components of a CCS project including pipeline integration and operation, providing the electric power industry with real-world experience in identifying and solving integration issues before moving to the costly commercial scale. This project was challenging from the standpoint of the multiple partners and their roles and associated legal agreements. Many of these agreements are consistent of commercial projects but many were the result of the R&D nature of the project. Perhaps the most valuable project relationship is that of a large electrical utility (Southern Company) supplying anthropogenic CO_2 captured at a coal-fired power plant to an oil company (Denbury) for geologic storage. The project in many respects mimics the process for developing a future CCUS relationship and strategy whereby anthropogenic CO_2 in used for enhanced oil recovery.

This project clearly benefitted from the existing base of CO_2 pipeline knowledge that Denbury brought to the project team; knowledge based on experiences with CO_2-EOR related to design, construction, and permitting. These included wetland and sensitive ecosystem/endangered species mitigation through the use of different pipeline installation techniques. An experienced permitting team and a thorough review of all potentially required permits allowed the project to develop and progress smoothly. A significant portion of the pipeline route outside the plant parallels an existing high voltage transmission corridor that simplified contracts for land access, allowing for a construction easement that minimized environmental impacts and project costs. The utilization of an existing transmission right-of-way was a benefit to the project.

The most challenging part of the project dealt with issues related to integration and operations. These issues include planned and forced plant outages, load following, fuel dispatch, and monitoring for CO_2 purity. Since the carbon capture plant separates CO_2 from the flue gas supplied by one of the several coal-fired boilers at the power plant, any interruption to either the coal plant or the capture plant impacted the supply of CO_2 for the injection project. Another issue was that of unit dispatch. In times of low electricity demand, the coal boilers may not dispatch at all. The price of natural gas and the availability of gas generation at Plant Barry played into dispatch. To date, no issues related to CO_2 purity have impacted CO_2 supply or pipeline/injection operations. Some limited interruptions occurred with the CO_2 booster pump for injection operation did occur in start-up operations.

Various utility business models, in different geographic regions, will ultimately drive the construction and complexity of CO_2 pipelines regionally throughout the USA (15). In some regions, captured CO_2 from emission sources will coincide locally with suitable geologic sinks. In other regions, CO_2 may be transported with a sole source pipeline to a single storage site, or, become incorporated into existing EOR pipelines network that accumulates multiple CO_2 sources (16) (17). Either way a firm understanding of the integration issues of captured anthropogenic CO_2 at coal-fired power plants with downstream injection operation whether for CCS or CCUS are important. In the USA Class VI well permitting requirements could also impact the operations of CO_2 pipelines serving saline storage projects. These regulatory issues must be fully understood because the same regulations that require CCS, would limit venting of anthropogenic CO_2 to the atmosphere.

Acknowledgements

Denbury Resources, owner and operator of Citronelle Field, is gratefully acknowledged for their essential contributions to the development of the CO_2 pipeline including Pat Moore, Jason Davis, West Richardson, and Tommy Miller. The authors also acknowledge Alabama Power Company Corporate Real-estate and Transmission Line Services including Johnny Dyess and James Weninegar in their key role in facilitating the construction easement on the Plant Barry plant site and on the electrical transmission corridor to the injection site. The authors also acknowledge the leadership and technical expertise of the Southern States Energy Board (SSEB) and the Electric Power Research Institute (EPRI) with respect to the management of the Regional Carbon Sequestration – Southeastern Regional Carbon Sequestration Partnership (SECARB) program.

This paper is based upon work in-part supported by the Department of Energy National Energy Technology Laboratory under DE-FC26-04NT42590. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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